Chapter 12
Operation and Maintenance Considerations

12-1. Introduction

This chapter discusses the maintenance aspects of lubrication. Detailed discussions cover maintenance scheduling; relative cost of lubricants; essential oil properties that must be retained to ensure adequate lubrication of equipment; degradation of lubricating oils, hydraulic fluids, and insulating transformer oils; particulate, water, and biological contamination; monitoring programs, including trend monitoring and oil testing; storage and handling; and environmental impacts.

12-2. Maintenance Schedules

a. Modern maintenance schedules are computer-generated, and are frequently referred to as computer maintenance management systems (CMMS). These systems are essential in organizing, planning, and executing required maintenance activities for complex hydropower, pumping, and navigation facilities. A complete discussion of CMMS is beyond the scope of this manual. Some Corps of Engineers and Bureau of Reclamation facilities recognize the value of CMMS and are currently using these systems to document operation and maintenance activities. The following discussion summarizes some key concepts of CMMS.

b. The primary goals of a CMMS include scheduling resources optimizing resource availability and reducing the cost of production, labor, materials, and tools. These goals are accomplished by tracking equipment, parts, repairs, and maintenance schedules.

c. The most effective CMMS are integrated with a predictive maintenance program (PdM). This type of program should not be confused with preventive maintenance (PM), which schedules maintenance and/or replacement of parts and equipment based on manufacturer's suggestions. A PM program relies on established service intervals without regard to the actual operating conditions of the equipment. This type of program is very expensive and often results in excess downtime and premature replacement of equipment.

d. While a PM program relies on elapsed time, a PdM program relies on condition monitoring of machines to help determine when maintenance or replacement is necessary. Condition monitoring involves the continuous monitoring and recording of vital characteristics that are known to be indicative of the machine's condition. The most commonly measured characteristic is vibration, but other useful tests include lubricant analysis, thermography, and ultrasonic measurements. The desired tests are conducted on a periodic basis. Each new measurement is compared with previous data to determine if a trend is developing. This type of analysis is commonly referred to as trend analysis or trending, and is used to help predict failure of a particular machine component and to schedule maintenance and order parts. Trending data can be collected for a wide range of equipment, including pumps, turbines, motors, generators, gearboxes, fans, compressors, etc. The obvious advantage of condition monitoring is that failure can often be predicted, repairs planned, and downtime and costs reduced.

12-3. Relative Cost of Lubricants

Cost is one of the factors to be considered when selecting lubricants. This is especially true when making substitutions such as using synthetics in place of mineral oils. Tables 12-1 and 12-2 provide basic

Table 12-1
Relative Cost of Vegetable and Synthetic Oils

Lubricant	Relative Cost to Mineral Oil[1,2]
Vegetable Oils[1]	2 - 3
Synthetic Fluids[2]	
Polybutenes	2
Polyalphaolefins	3
Dialkylbenzene	5
Polyalkyline glycols	3 - 5
Polyol esters	3 - 5
Diesters	2 - 6
Phosphate esters	4 - 7
Cycloaliphatics	9 - 15
Silicone fluids	12 - 24
Silicate esters	33 - 45
Halogenated hydrocarbons	100 - 450
Polyphenyl ethers	625 - 700

[1] Rhee, 1996 (Vegetable oils).
[2] Straiton, 1998 (Synthetic fluids).

Table 12-2
Relative Cost of Greases

Grease Type	Base Oil	Relative Cost to Lithium Grease [1]
Aluminum	Mineral	2.5 - 3
Calcium	Mineral	0.8
Lithium	Mineral	1
Sodium	Mineral	0.9
Aluminum complex	Mineral	2.5 - 4
Calcium complex	Mineral	0.9 - 1.2
Lithium complex	Mineral	2
Sodium complex	Mineral	3.5
Lithium	Ester	5 - 6
Lithium complex	Ester	10
Lithium complex	Silicone	20
Bentonites (organo clay)	Mineral	2 - 6
Polyurea	Mineral	3
Polyurea	Silicone	35 - 40
Polyurea	Fluorosilicone	100

[1] Mancuso and South 1994.

information on the relative cost of various lubricants. Reference to these tables and charts reveals that synthetic lubricants are considerably more expensive than mineral lubricants. Therefore, justification for their use must be based on operating requirements for which suitable mineral lubricants are not available.

12.4. Lubricating Oil Degradation

A lubricating oil may become unsuitable for its intended purpose as a result of one or several processes. Most of these processes have been discussed in previous chapters, so the following discussions are brief summaries.

a. Oxidation. Oxidation occurs by chemical reaction of the oil with oxygen. The first step in the oxidation reaction is the formation of hydroperoxides. Subsequently, a chain reaction is started and other compounds such as acid, resins, varnishes, sludge, and carbonaceous deposits are formed.

b. Water and air contamination. Water may be dissolved or emulsified in oil. Water affects viscosity, promotes oil degradation and equipment corrosion, and interferes with lubrication. Air in oil systems may cause foaming, slow and erratic system response, and pump cavitation.

(1) Results of water contamination in fluid systems

! Fluid breakdown, such as additive precipitation and oil oxidation

! Reduced lubricating film thickness

! Accelerated metal surface fatigue

! Corrosion

! Jamming of components due to ice crystals formed at low temperatures

! Loss of dielectric strength in insulating oils.

(a) Effects of water on bearing life. Studies have shown that the fatigue life of a bearing can be extended dramatically by reducing the amount of water contained in a petroleum based lubricant. See Table 12-3.

(b) Effect of water and metal particles. Oil oxidation is increased in a hydraulic or lubricating oil in the presence of water and particulate contamination. Small metal particles act as catalysts to rapidly increase the neutralization number of acid level. See Table 12-4.

Table 12-3
Effect of Water on Bearing Fatigue Life

Lubricant	Water Concentration	Relative Life Factor
SAE 20	25 ppm	4.98
SAE 20	100 ppm	1.92
SAE 20	400 ppm	1.00

Reference: Effect of Water in Lubricating Oil on Bearing Life, 31st annual ASLE meeting, 1975.

Table 12-4
Effect of Water and Metal Particles on Oil Oxidation

Run	Catalyst	Water	Hours	Total Acid* Number Change
1	None	No	3500+	0
2	None	Yes	3500+	+0.73
3	Iron	No	3500+	+0.48
4	Iron	Yes	400	+7.93
5	Copper	No	3000	+0.72
6	Copper	Yes	100	+11.03

*Total acid number increases that exceed 0.5 indicate significant fluid deterioration.
Reference: Weinshelbaum, M., Proceedings, National Conference on Fluid Power, VXXXIII:269.

(2) Sources of Water Contamination

! Heat exchanger leaks

! Seal leaks

! Condensation of humid air

! Inadequate reservoir covers

! Temperature drops changing dissolved water to free water.

(3) Forms of water in oil

! Free water (emulsified or droplets)

! Dissolved water (below saturation level).

(4) Typical oil saturation levels

! Hydraulic--200 to 400 ppm (0.02 to 0.04%)

! Lubricating--200 to 750 ppm (0.02 to 0.075%)

! Transformer--30 to 50 ppm (0.003 to 0.005%).

(5) Results of Dissolved Air and Other Gases in Oils

! Foaming

! Slow system response with erratic operation

! A reduction in system stiffness

- Higher fluid temperatures
- Pump damage due to cavitation
- Inability to develop full system pressure
- Acceleration of oil oxidation

c. Loss of additives. Two of the most important additives in turbine lubricating oil are the rust- and oxidation-inhibiting agents. Without these additives, oxidation of oil and the rate of rusting will increase.

d. Accumulation of contaminants. Lubricating oil can become unsuitable for further service by accumulation of foreign materials in the oil. The source of contaminants may be from within the system or from outside. Internal sources of contamination are rust, wear, and sealing products. Outside contaminants are dirt, weld spatter, metal fragments, etc., which can enter the system through ineffective seals, dirty oil fill pipes, or dirty make-up oil.

e. Biological deterioration. Lubricating oils are susceptible to biological deterioration if the proper growing conditions are present. Table 12-5 identifies the type of “infections” and associated characteristics. Hydraulic oils are also susceptible to this type of deterioration. These are discussed in paragraph 12-5. Procedures for preventing and coping with biological contamination include cleaning and sterilizing, addition of biocides, frequent draining of moisture from the system, avoidance of dead-legs in pipes.

Table 12-5
Characteristics of Principal Infecting Organisms (Generalized Scheme)

Organism	pH Relationship	Products of Growth	Type of Growth
Aerobic bacteria (use oxygen)	Prefer neutral to alkaline pH.	Completely oxidized products (CO_2 and H_2O) and some acids. Occasionally generate ammonia.	Separate rods, forming slime when agglomerated. Size usually below 5 μm in length (1.64×10^{-5} ft)
Anaerobic bacteria (grow in absence of oxygen)	Prefer neutral to alkaline pH	Incompletely oxidized and reduced products including CH_4, H_2, and H_2S.	As above. Often adhere to steel surfaces, particularly swarf
Yeasts	Prefer acid pH.	Oxidized and incompletely oxidized products. pH falls.	Usually separate cells, 5-10 μm (1.64×10^{-5} ft to 3.28×10^{-5} ft), often follow bacterial infections or occur when bacteria have been inhibited. Sometimes filamentous.
Fungi (molds)	Prefer acid pH, but some flourish at alkaline pH in synthetic metal working fluids.	Incompletely oxidized product organic acids accumulate.	Filaments of cells forming visible mats of growth. Spores may resemble yeasts. Both yeasts and molds grow more slowly than bacteria.

12.5 Hydraulic Oil Degradation

a. Water contamination.

(1) Due to the hygroscopic nature of hydraulic fluid, water contamination is a common occurrence. Water may be introduced by exposure to humid environments, condensation in the reservoir, and when

adding fluid from drums that may have been improperly sealed and exposed to rain. Leaking heat exchangers, seals, and fittings are other potential sources of water contamination.

(2) The water saturation level is different for each type of hydraulic fluid. Below the saturation level water will completely dissolve in the oil. Oil-based hydraulic fluids have a saturation level between 100 and 1000 ppm (0.01% to 0.1%). This saturation level will be higher at the higher operating temperatures normally experienced in hydraulic systems.

b. Effects of water contamination. Hydraulic system operation may be affected when water contamination reaches 1 to 2%.

(1) Reduced viscosity. If the water is emulsified, the fluid viscosity may be reduced and result in poor system response, increased wear of rubbing surfaces, and pump cavitation.

(2) Ice formation. If free water is present and exposed to freezing temperatures, ice crystals may form. Ice may plug orifices and clearance spaces, causing slow or erratic operation.

(3) Chemical reactions.

(a) Galvanic corrosion. Water may act as an electrolyte between dissimilar metals to promote galvanic corrosion. This condition first occurs and is most visible as rust formations on the inside top surface of the fluid reservoir.

(b) Additive depletion. Water may react with oxidation additives to produce acids and precipitates that increase wear and cause system fouling. Antiwear additives such as zinc dithiophosphate (ZDTP) are commonly used for boundary lubrication applications in high-pressure pumps, gears, and bearings. However, chemical reaction with water can destroy this additive when the system operating temperature rises above 60 $^\circ$C (140 $^\circ$F). The end result is premature component failure due to metal fatigue.

(c) Agglomeration. Water can act as an adhesive to bind small contaminant particles into clumps that plug the system and cause slow or erratic operation. If the condition is serious, the system may fail completely.

(d) Microbiological contamination. Growth of microbes such as bacteria, algae, yeast, and fungi can occur in hydraulic systems contaminated with water. The severity of microbial contamination is increased by the presence of air. Microbes vary in size from 0.2 to 2.0 µm for single cells and up to 200 µmM for multicell organisms. Under favorable conditions, bacteria reproduce exponentially. Their numbers may double in as little as 20 minutes. Unless they are detected early, bacteria may grow into an interwoven mass that will clog the system. A large quantity of bacteria also can produce significant waste products and acids capable of attacking most metals and causing component failure.

12-6. Transformer and Circuit Breaker Insulating Oil Degradation

a. The consequences of oil degradation in a transformer can be even more serious than with other equipment. Combustible gases may form as the transformer develops faults. Some gases are present in a dissolved state while others are found in the free space of the transformer. The type and concentration of gases and the ratio in which they are present are commonly used to assess the serviceable condition of transformers. Under the right conditions these gases may explode, causing significant damage and injury to personnel. The testing of transformer oils and assessment of transformer serviceable conditions has become a specialty. The Bureau of Reclamation has published a manual that provides detailed procedures and criteria for testing insulating oils. The reader should refer to Reclamation Facilities Instructions, Standards, and Techniques (FIST) publication Volume 3-5, "Maintenance of Liquid Insulation Mineral Oils and Askarels" for detailed information on transformer and circuit breaker oil maintenance and testing. For information on monitoring, testing, and assessment of transformer serviceability, refer to IEEE Standard C57.104-1991, "IEEE Guide for the Interpretation of Gases."

b. Transformer and circuit-breaker insulating oils suffer degradation similar to that of lubricating oil and hydraulic fluid including as oxidation, sludge formation, additive depletion, and moisture contamination. Sludge can significantly affect the flow of heat from the oil to the coolant and from the core and coils to the cooling coil. If these conditions are prolonged, the excessive temperature and heat can damage the transformer insulation and eventually cause short circuits and breakdown of the transformer. Moisture can be present in three forms: dissolved, emulsified, or free state. Emulsified water is especially harmful since it has significant influence in reducing the dielectric strength of the oil. Another form of contamination is the presence of dissolved nitrogen, which can cause problems due to corona discharge. Circuit breakers may have all the above problems plus the formation of carbon particles, which can cause short circuits.

12.7. Essential Properties of Oil

Several important properties of used oil must be retained to ensure continued service, as discussed below.

a. Viscosity. New turbine oils are sold under the International Standards Organization (ISO) Viscosity Grade System. Oil manufacturers normally produce lubricating oil with viscosity of ISO-VG-22, VG-32, VG-46, VG-68, VG-100, VG-150, VG-220, VG-320, and VG-460. The numbers 22 through 460 indicate the average oil viscosity in centistoke units at 40°C (104 °F) with a range of ±10 percent. Most hydroelectric power plants use ISO-VG -68 or ISO-VG-100 oils.

b. Oxidation stability. One of the most important properties of new turbine oil is its oxidation stability. New turbine oils are highly stable in the presence of air or oxygen. In service, oxidation is gradually accelerated by the presence of a metal catalyst in the system (such as iron and copper) and by the depletion of antioxidant additives. Additives control oxidation by attacking the hydroperoxides (the first product of the oxidation step) and breaking the chain reaction that follows. When oxidation stability decreases, the oil will undergo a complex reaction that will eventually produce insoluble sludge. This sludge may settle in critical areas of the equipment and interfere with lubrication and cooling functions of oil. Most rust inhibitors used in turbine oils are acidic and contribute to the acid number of the new oil. An increase in acid number above the value for new oil indicates the presence of acidic oxidation products or, less likely, contamination with acidic substances. An accurate determination of the total acid number (TAN) is very important. However, this test does not strictly measure oxidation stability reserve, which is better determined by the Rotating Bomb Oxidation Test (RBOT), ASTM Test Method D 2272.

c. Freedom from sludge. Sludge is the byproduct of oil oxidation. Due to the nature of the highly refined lubricant base stocks used in the manufacture of turbine oils, these oils are very poor solvents for sludge. This is the main reason why the oxidation stability reserve of the oil must be carefully monitored. Only a relatively small degree of oxidation can be permitted; otherwise, there is considerable risk of sludge deposition in bearing housings, seals, and pistons. Filtration and centrifugation can remove sludge from oil as it is formed, but if oil deterioration is allowed to proceed too far, sludge will deposit in parts of the equipment, and system flushing and an oil change may be required.

d. Freedom from abrasive contaminants. The most deleterious solid contaminants found in turbine oil systems are those left behind when the system is constructed and installed or when it is opened for maintenance and repair. Solid contaminants may also enter the system when units are outdoors, through improperly installed vents, and when units are opened for maintenance. Other means of contamination are from the wearing of metals originating within the system, rust and corrosion products, and dirty make-up oil. The presence of abrasive solids in the oil cannot be tolerated since they will cause serious damage to the system. These particles must be prevented from entering the system by flushing the system properly and using clean oil and tight seals. Once abrasive solids have been detected, they must be removed by filtration or centrifugation, or both.

e. Corrosion protection. The corrosion protection provided by the lubricant is of significant importance for turbine systems. New turbine oil contains a rust-inhibitor additive and must meet ASTM Test Method D 665. The additive may be depleted by normal usage, removal with water in the oil, absorption on wear particles and debris, or chemical reaction with contaminants.

f. Water separability. Water can enter the turbine lubricating oil system through cooler leaks, by condensation, and, to a lesser degree, through seal leaks. Water in the oil can be in either the dissolved or insoluble form. The insoluble water may be in the form of small droplets dispersed in the oil (emulsion) or in a separate phase (free state) settled at the bottom of the container. Water can react with metals to catalyze and promote oil oxidation. It may deplete rust inhibitors and may also cause rusting and corrosion. In addition to these chemical effects on the oil, additives, and equipment, water also affects the lubrication properties of the oil. Oil containing large amounts of water does not have the same viscosity and lubricating effect of clean oil. Therefore, turbine lubricating oil should not contain a significant amount of free or dispersed water. Normally, if the oil is in good condition, water will settle to the bottom of the storage tank, where it should be drained off as a routine operating procedure. Water may also be removed by purification systems. If turbine oil develops poor water separability properties (poor demulsibility), significant amounts of water will stay in the system and create problems. The water separability characteristics of an oil are adequately measured using the ASTM Test Method D 1401 procedure. Insoluble water can be removed by filtration and centrifugation.

12-8. Other Properties of Used Oils

Other properties of lubricating oil that are important, but for which direct measurement of their quantitative values is less significant, are described below.

a. Color. New turbine oils are normally light in color. Oil will gradually darken in service. This is accepted. However, a significant color change occurring in a short time indicates that something has changed. For example, if oil suddenly becomes hazy, it is probably being contaminated with water. A rapid darkening or clouding may indicate that oil is contaminated or excessively degraded.

b. Foaming characteristics. Foaming characteristics are measured by ASTM Test Method D 892. This test will show the tendency of oil to foam and the stability of the foam after it is generated. Foaming can result in poor system performance and can cause serious mechanical damage. Most lubricants contain antifoam additive to break up the foam.

c. Water content. Turbine oil should be clear and bright. Most turbine oil will remain clear up to 75 ppm water at room temperature. A quick and easy qualitative analysis of insoluble water in oil is the hot plate test. A small amount of oil is placed on a hot plate. If oil smokes, there is no insoluble water. If it spatters, the oil contains free or suspended water.

d. Inhibitor content. The stability of turbine lubricating oil is based on the combination of high-quality base stock with highly effective additives. Therefore, it is very important to monitor the oxidation of the turbine oil. ASTM Test Method D 2272 (RBOT) is very useful for approximating the oxidation inhibitor content of the turbine oil. The remaining useful life of the oil can be estimated from this test.

e. Wear and contaminant metals. Quantitative spectrographic analysis of used oil samples may be used to detect trace metals (and silica) and identify metal-containing contaminants. System metals such as iron and copper can be accurately identified if the sample is representative and the metals are solubilized or are very finely divided. A high-silica level generally indicates dirt contamination.

12-9. Oil Monitoring Program

Periodic oil testing can measure the effects of oxidation, and detect the types and amount of various contaminants in the oil. Periodic testing can provide early detection of problems within a lubricating system; determine whether the oil is still serviceable; and provide information to prepare a filtering or purification schedule. By monitoring the condition of the oil, premature equipment failure due to oil deterioration can be prevented. Various standard tests are available depending on the type of oil and service. Table 12-6 briefly identifies and compares the various analysis methods available, and their benefits and limitations. Table 12-7 shows that each category of oil analysis is well suited to provide important information, but no single test can provide complete information about the causes of lubricant deterioration. The appropriate tests must be conducted to obtain the information desired. Field tests can

Table 12-6
Fluid Analysis Methods

Method	Units	Benefits	Limitations
Optical particle count	Number/ml	Accurate size and quantity distribution	Sample preparation time
Automatic particle count	Number/ml	Fast, repeatable	Sensitive to particle concentration and nonparticulate contaminants, e.g., water, air, gels
Patch test and fluid contamination comparator	Visual comparison/ cleanliness code	Rapid analysis of fluid cleanliness levels in field; helps to identify type of contaminant	Provides approximate contamination levels
Ferrography	Scaled number of large/small particles	Basic information which will indicate the need for more sophisticated testing upon abnormal results	Cannot detect nonferrous particles, e.g., brass, copper, silica etc.
Spectrometry	ppm	Identifies and quantifies contaminant material	Cannot size contaminants; limited sensitivity above 5 µm (1.64×10^{-5} ft).
Gravimetric	mg/l	Indicates total amount of contaminant	Cannot distinguish particle size; when comparing samples, sensitivity is limited to extremely large differences in particulate level

Reference: Contamination Control and Filtration Fundamentals, Pall Corporation, Glen Cove, NY.

Table 12-7
Categories of Oil Analysis

What is being analyzed / Possible tests	Fluid Properties (Physical and chemical properties of used oil) (aging process)	Contamination (Fluid and machine destructive contaminants)	Wear Debris (Presence and identification of particles)
Particle counting	NB	PB	MB
Moisture analysis	NB	PB	NB
Viscosity analysis	PB	MB	NB
Wear debris density	NB	NB	PB
Analytical ferrography	NB	MB	PB
TAN/TBN	PB	MB	MB
FTIR	PB	MB	NB
Patch test	NB	PB	MB
Flash point test	MB	PB	NB
Elemental Analysis	PB	MB	PB

Note: PB - Primary Benefit, MB - Minor Benefit, NB - No Benefit
Reference: Reprinted by permission of Noria Corporation, Tulsa, OK

be performed to expedite assessment of an oil's condition. However, field testing is not as complete or as accurate as laboratory analysis. Generally, laboratory tests should be performed to confirm field test results. Project personnel should establish a monitoring program for their lubricating oils. This program should include sampling and testing of significant oil properties at appropriate intervals, logging, interpretation of test data, and action steps. In this section and in the discussion of sampling technique, recommendations on properties to be tested, testing intervals, ASTM test methods, and action steps to correct the problems are discussed.

a. Sampling and testing schedule.

(1) Sample collection. The sample should be drawn into clean oil bottles or oil-compatible containers while the equipment is operating at normal temperature or immediately after shutdown. To minimize sample contamination, bottle suppliers can provide bottles in three levels of cleanliness: clean (fewer than 100 particles greater than 10 µm/ml (fewer than 100 particles in 1 ml (0.00026 gal) greater than 10 µm (3.28×10^{-6} ft)), superclean (fewer than 10), and ultraclean (fewer than 1). The sample should be labeled immediately with the date it was taken, the source, and the type and brand name of the lubricant.

(a) Lubricating oil. The oil sample must be representative of oil in the system. The preferred sampling location is in the return lines upstream of filters. If a static oil sample must be drawn, a drop-tube static sampling setup should be used to prevent contamination with sludge from the bottom of the sump. If oil must be drawn from a tap on the oil sump, wipe the tap and let sufficient oil flow to clear stagnant oil from the tap before taking the actual test sample.

(b) Hydraulic oil. The preferred sampling location is in the return line immediately upstream from the return-line filter. This location will sample particles circulating in the system. An alternative location is the supply line directly downstream from the pump. Extracting samples from the reservoir is not recommended except when no other choice is available. When necessary, reservoir samples should be taken midway between the surface and bottom of the reservoir. To ensure the most accurate results and to develop meaningful trends, all samples should be taken from the same location, in the same manner, and under the same conditions. Do not compare samples drawn from an operating machine with samples from a stationary machine.

(c) Transformer and circuit breaker insulating oil. Sampling procedures for transformer and circuit breaker insulating oils are covered in Reclamation FIST manual entitled “Maintenance of Liquid Insulation Mineral Oils and Askarels”.

(2) Field testing. Many oil properties can be field-tested economically and with relatively simple procedures and equipment. Suspicious test results should be verified by more comprehensive laboratory analysis. The following procedures are intended for oils other than those used in transformers and circuit breakers.

(a) Visual test. A visual inspection of an oil sample is the simplest type of field test. Table 12-8 outlines the procedures for conducting a visual test of oil samples. The sample to be inspected should be stored at room temperature away from direct sunlight for at least 24 hours before the inspection. The sample should be checked for sediment, and separated water. Oils also may have unusual color cloudiness or unusual odors. For comparison, it is a good idea to keep a sample of new unused oil of the same type and manufacturer stored in a sealed container in a cool dark place. The used sample can then be compared with the new sample with respect to color, odor, and general appearance.

(b) Water contamination. Hazy or cloudy oil may indicate water contamination. The “crackle” test is a simplified procedure that can be used to verify the presence of water in oil, but the test does not provide quantitative results. The crackle test can be conducted by making a small cup from aluminum foil, adding a few drops of the oil, and heating rapidly over a small flame. The test can also be conducted by using a hot plate, as previously noted, or by immersing a hot soldering iron in a sample of the oil. An audible crackling sound will be heard if water is present. Eye protection should be worn during the test to prevent injury if oil splatters during the heating. If water contamination is evident, the oil should be purified and a sample of the purified oil should be sent to a laboratory for analysis. If sediment is present, the oil should be purified, and samples of both the unpurified oil and the purified oil should be submitted for analysis. The sediment of the unpurified oil can be analyzed to determine its source.

(c) Microbial contamination. Initial microbial contamination of hydraulic fluids may also be detected by a foul odor due to waste and decomposition products of the microbes. Fluid viscosity may appear thicker due to the microbes. Fluid color may range from a light brown to a slimy green appearance.

(d) Neutralization number. An oil's neutralization number can also be determined in the field. With the exception of some motor oils, which may be alkaline, most lubricating oils are essentially neutral. An acidic oil is probably the result of oxidation due to extended service or abnormal operating conditions. The neutralization number of new oil is usually less that 0.08. The maximum allowable number depends on the type of oil and service, and this number should be obtained from the oil manufacturer. The maximum value is usually less than 0.5. Of greatest concern in this test is the rate of increase, not necessarily the neutralization number itself. A sudden increase in the neutralization number may indicate that an operational problem exists or that the oil has reached the end of its useful life. In either case, action is required to prevent further deterioration and equipment damage. If tests show a large increase in the neutralization number, or if the neutralization number exceeds the maximum value allowable, the oil manufacturer should be consulted to determine if the oil can be economically reclaimed.

Table 12-8
Visual Examination of Used Lubricating Oil

Appearance of Sample			Action To Be Taken	
When Taken	**After 1 hour**	**Reason**	**System without filter(1) or centrifuge**	**System with filter (1) or centrifuge**
Clear	---	---	None	None
Opaque(2)	Clear	Foaming	Cause of foaming to be sought (3)	Cause of foaming to be sought (3)
	Clear oil with separated water layer	Unstable emulsion(4)	Runoff water (and sludge) from drain(5)	Check centrifuge(6)
	No change	Stable emulsion	Submit sample for analysis(7)	Check centrifuge:(6) if centrifuge fails to clear change oil
Dirty	Solids separated(8)	Contamination	Submit sample for analysis(7)	Check filter or centrifuge
Black (acrid smell)	No change	Oil oxidized	Submit sample for analysis(7)	Submit sample for analysis(7)

1. Take sample of circulating oil in clean glass bottle (50-100 ml).
2. If dirty or opaque, stand for 1 hour, preferably at 60° C (an office radiator provides a convenient source of heat).

Notes:
(1) The term filter is restricted to units able to remove particles less than 50 µm; coarse strainers, which are frequently fitted in oil pump suctions to protect the pump, do not remove all particles liable to damage bearings, etc.
(2) Both foams (mixtures of air and oil) and emulsions (mixtures of water and oil) render the oil opaque.
(3) Foaming is usually mechanical in origin, being caused by excessive churning, impingement of high-pressure return oil on the reservoir surface, etc. Foam can be stabilized by the presence of minor amounts of certain contaminants, e.g., solvents, corrosion preventives, grease. If no mechanical reason can be found for excessive foam generation, it is necessary to change oil.
(4) Steps should be taken to remove the water as soon as possible. Not only is water liable to cause lubrication failure, but it will also cause rusting; the presence of finely divided rust tends to stabilize emulsions.
(5) Failure of water to separate from oil in service may be the result of inadequate lubricant capacity or the oil pump suction being too close to the lowest part of the reservoir. More commonly, it results from re-entrainment of separated water from the bottom of the sump when, by neglect, it has been allowed to build up in the system.
(6) The usual reason for a centrifuge failing to remove water is that the temperature is too low. The oil should be heated to 80 °C (176 °F) before centrifuging.
(7) It is not always possible to decide visually whether the oil is satisfactory or not. In doubtful cases, it is necessary to have laboratory analysis.
(8) In a dark oil, solids can be seen by inverting the bottle and examining the bottom.

Reference: Neale, M. J., Lubrication - A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

(e) Particle counting. Portable particle counters are available for in-house testing. The advantage is that measurement results can be obtained quickly, as opposed to the 1- to 2-week waiting period typical for laboratory testing. The quick results also allow timely preventive measures to reduce the potential for severe damage. Two types of portable particle counters are generally available: laser and differential pressure. Laser counters transmit a light beam through the fluid to a photodetector on the opposite side. The light intensity measured varies with the number of particles in the fluid. As the number of particles increases, the light scattering increases and the light intensity measured at the detector is reduced. The intensity of the measured light is an indication of the number of particles in the fluid sample. Laser counters are accurate and can measure a particle to 2 µm (6.56×10^{-6} ft). Laser counters have several disadvantages, including sensitivity to other conditions that may restrict light passage through the fluid: aeration, haziness (typically caused by water), fluid opacity, and emulsions. The differential particle counter measures differential pressure across standard 5- and 15-µm (1.64×10^{-5} and 4.96×10^{-5} ft) screens, which correlate with ISO particle counting standards. As fluid passes through the screens, large particles are filtered, causing the differential pressure across the screens to increase. This type of counter is not affected by the disadvantages that affect laser counters.

(3) Laboratory testing and analysis. When field testing is inadequate or indicates that additional testing is required, oil samples should be submitted for laboratory analysis. Laboratory analysis should include viscosity, neutralization number, water contamination, and the identification of wear metal and other contaminants. Properties to be tested, along with the ASTM test method to be used, are listed in Table 12-9. If possible, the oil's manufacturer should perform tests periodically. Since the composition and additive content of oils is usually considered proprietary information, only the manufacturer can accurately determine the extent of additive depletion. When analysis is conducted by independent laboratories, the oil manufacturer should be contacted anytime the test results suggest questionable serviceability of an oil. When problems arise or abnormal situations develop, other properties may be tested or the testing frequency of the recommended properties should be increased. For example, if oil color suddenly becomes hazy or dark, the oil should be tested immediately for water or other contamination. The tests included in Table 12-9 are used to determine contamination and degradation of the oil. Viscosity, appearance, water content, and cleanliness are related to contamination. Total acid number (TAN), color, and Rotating Bomb Oxidation Test (RBOT) are related to degradation. The RBOT and TAN tests are excellent for following the degradation of turbine oil. If RBOT results for the new oil are known, these can be compared with the values for the used oil to determine the oxidation stability reserve of the used oil. Changes in the RBOT and TAN of the oils are the best indication of the remaining useful life of the lubricating oil.

Table 12-9
Key Tests for Oil Quality Control Monitoring

Property Test	ASTM Test Method
Total acid number (TAN)	D 664, D 974
Color	D 1500
Appearance	Visual
Viscosity	D 445
Rotating Bomb Oxidation Test (RBOT)	D 2272
Water content	D 95, D 1744
Rust test	D 665A
Cleanliness	Particle Counter, F 311 and F 312

(4) Test frequencies

(a) New oil. Oil should be tested prior to filling the unit and retested 3 months later. Sampling should continue at this interval until a trend is established. The sampling interval can then be extended as dictated by the test results.

(b) Installation of new components. When new components are installed the above oil testing frequency should be followed.

(c) Normal operation. Equipment maintenance records should suggest oil sampling frequencies. Additional testing should be conducted on a periodic basis, and at increased frequencies as dictated by the oil analysis results. In the absence of recommended sampling frequencies, 500 hours is commonly suggested for journal and roller bearing lubricant applications. Oil samples should be drawn from governors and all guide and thrust bearings annually and submitted for laboratory analysis. In addition to the annual tests, samples should be visually inspected at frequent intervals. Test oil annually or more often if conditions warrant. If oil appears clean and no operational problems have been noted, testing may be postponed to the next unit overhaul. When a unit is overhauled, test the oil before draining into a storage tank. If oil is degraded, discard it to prevent storage tank contamination.

(d) Logging and interpretation of test data. It is important to keep accurate records of test results. Properties that change as the oil degrades, such as viscosity, oxidation, TAN, and RBOT, should be graphed to provide a visual indication of relative changes or trends. This procedure highlights any unusual trends and allows for a more accurate estimate of the remaining service life of lubricating oil. Oil properties can be affected by routine addition of make-up oil and by the type of oil added. Whenever a reservoir is topped, the data baseline must be reset to prevent erroneous interpretation of trend results.

(e) Recommended corrective action. The primary purpose of an oil monitoring program is to ensure long, trouble-free operation of the turbine and generators, main pumps and motors, or other equipment. To achieve this purpose, the monitoring program must include prompt and appropriate action steps. The corrective action must be based on correct interpretation of the test data, as outlined in Tables 12-10 and 12-11. It is very important to follow the monitoring schedule that has been established. Interpretation is more meaningful if the data have been collected over an extended period of time.

12-10. Oil Purification and Filtration

a. Cleanliness.

(1) Oil must be free of contaminants to perform properly. Most hydraulic systems use an in-line filter to continually filter the oil while the system is operating to maintain the required cleanliness rating in accordance with ISO standards (Table 12-12). ISO 4406 is an internationally recognized standard that expresses the level of particulate contamination of a hydraulic fluid. The standard is also used to specify the required cleanliness level for hydraulic components and systems. ISO 4406 is a hydraulic cleanliness rating system that is based on a number of contamination particles larger than 2 microns, 5 microns, and 15 microns in a 1-milliliter fluid sample. Once the number and size of the particles are determined, the points are plotted on a standardized chart of ISO range numbers to convert the particle counts into an ISO 4406 rating. The ISO 4406 rating provides three range numbers that are separated by a slash, such as 16/14/12. In this rating example, the first number 16 corresponds to the number of particles greater than 2 microns in size; the second number 14 corresponds to the number of particles greater than 5 microns in size; and the third number 12 corresponds to the number of particles greater than 15 microns in size. All three values for applicable range numbers can be determined through the use of the ISO 4406 standardized chart based on the actual number of particles counted within the 1-milliliter (ml) sample for each size category (>2, >5, >15 microns). For example, if a 1-ml sample contained 6000 2-mm particles, 140 5-mm particles, and 28 15-mm particles, the fluid would have a cleanliness rating of 20/14/12. The number of 2-mm particles (6000) falls in the range greater than 5000 but less than 10,000, which results in an ISO 4406 range number of 20. The number of 5-m particles (140) falls in the range greater than 80 but less than 160, which results in an ISO 4406 range number of 14. The number of 15-mm particles (28) falls in the range greater than 20 but less than 40, which results in an ISO 4406 range number of 12.

Table 12-10
Interpretation of Test Data and Recommended Action

Test	Warning Limit	Interpretation	Action Steps
Total acid No. (TAN) increase, over new oil	0.1-0.5 mg KCH/g	This represents above-normal deterioration. Possible causes are anti-oxidant depletion or oil contamination.	Investigate cause. Increase frequency of testing; compare with RBOT data. Consult with oil supplier for possible reinhibition.
	Exceeds 0.5 mg KOH/g	Oil at or approaching end of service life: oil may be contaminated.	Look for signs of increased sediment on filters and centrifuge. Check RBOT. If RBOT less than 25 percent of original, review status with oil supplier and consider oil change. Increase test frequency if left in system.
RBOT2	Less than half value of original oil	Above-normal degradation.	Investigate cause. Increase frequency of testing.
	Less than 25 percent of original	Together with high TAN, indicates oil at or approaching end of service life.	Resample and retest. If same, change oil and consider discarding the oil.
Water content	Exceeds 0.2 percent	Oil contaminated: potential water leak	Investigate and remedy cause. Clean system by centrifugation. If still unsatisfactory, consider oil change or consult oil supplier
Cleanliness	Exceeds 0.01 percent volume, particulates	Source of particulates may be make-up oil, dust, or ash entering system. or wear condition in system.	Locate and eliminate source of particulates. Clean system oil by filtration or centrifugation, or both.
Rust test, Procedure A	Failure, light rusting	Possibilities: (a) the system is wet or dirty, or both, (b) the system is not maintained properly (for example, water drainage neglected, centrifuge not operating, or (c) additive depleted.	Investigate cause and make necessary maintenance and operating changes. Check rust test. Consult oil supplier regarding reinhibition if test result unchanged.
Appearance	Hazy	Oil contains water or solids, or both.	Investigate cause and remedy. Filter or centrifuge oil, or both.
Color	Unusual and rapid darkening	This is indicative of contamination or excessive degradation.	Determine cause and rectify.
Viscosity	±20 percent from original oil viscosity	Possibilities: oil is contaminated, or oil is severely degraded.	Determine cause. If viscosity is low, determine flash point. Consult oil supplier. Change oil, if necessary.
Flash point	Drop 30° F (-1° C) or more compared to new oil	Probably contamination.	Determine cause. Check other quality parameters. Consider oil change.
Foam test ASTM D 892, Sequence 1	Exceeds following limits: tendency - 450, stability - 10	Possibly contamination or antifoam depletion. In new turbines, residual rust preventatives absorbed by oil may cause problem.	Rectify cause. Check with oil supplier regarding reinhibition. (Note: plant problems are often mechanical in origin.)

1 Typical TAN value for new oil is 0.1 to 0.3 mg KOH/g.
2 Typical RBOT value for new oil is 250 min.
Reference: Reprinted by permission of Noria Corporation, Tulsa, OK.

(2) Table 12-13 shows the desirable cleanliness levels for different types of systems and typical applications rated by the system sensitivity, from noncritical systems through super-critical systems. Table 12-14 shows the desired ISO cleanliness code for specific components in hydraulic and lubricating systems.

Table 12-11
Oil Analysis Data Interpretation and Problem Indication

Problem Area	Analytical Indications[a]	Inspection/Sensory Indications[b]
Air entrainment	Increased viscosity, TAN[c], water, and/or FTIR[b] for oxidation Silicon defoamant levels too high/low Blotter test: cokelike carbon on patch	Oil clouding/foaming, increase in oil gage temperature. Spongy/slow hydraulics, cavitation of pump/bearing, noisy operation.
Abrasive wear conditions	Increased silicon, aluminum, particle count, and/or ferrous particles Water contamination Ferrogram has cutting wear, silica particles	Scratch marking or/polishing of frictional surfaces Cutting wear on blotter/patch/filter media Filter/breather/seal failure
Corrosive wear conditions	Increased TAN[c], particle count, spectrographic iron & bearing metals, water Decrease in TBN[d] Ferrogram shows submicron debris at ferrogram tail, rust particles, metal oxides	Fretting, pitting, and etching on contact surfaces Transient electric currents, high-engine blowby Rust on patch or filter media
Failed filter	Increasing silicon/aluminum, particle count, ferrous particles, and/or elemental iron Ferrograms show green-looking particles, cutting wear, filter fibers	Valve silt lock, noisy bearings Unchanging or high delta P of filter Frequent bearing failures, high levels of bottom sediment
Overheating	Increasing ferrous particles, particle count, flash point, viscosity, or oil specific gravity Ferrograms show friction polymers, oxides, bluing/tempering of particles, sliding wear particles, bearing particles, e.g., babbitt metal	Bearing distress/failure Hot spots and high bearing metal temperature Evidence of coking/sludge Burn/rancid odor, high oil gage temperature
Misalignment, imbalance, overloading	Ferrograms densely loaded with black-iron oxides, dark metal oxides, severe cutting and sliding wear, tempered particles, large, chunky particles, or bearing metals Increase in viscosity, TAN[c], particle count, and/or ferrous particles Depletion of Zn and P	Engine lugging/stalling, black exhaust Raised oil, bearing metal, or jacket-water temperature Dark, foul-smelling oil, bearing distress/failure, hard turning of shaft Abnormal vibration, noise Blotter test: coke, metal chips Metal chips on filter, highly loaded chip detectors
Impending failure of bearing, gear, pump, etc.	Exponential increase in particle count and number of wear particle concentration Increase in iron or bearing metals Ferrogram shows rate increase in spheres, dark metal oxides, particle bluing, spalling/chunks, severe sliding/galling particles, cutting wear	Shaft wobble, vibration, acoustic changes, blue exhaust smoke, hot spots, hard turning shaft, and/or high-bearing metal temperatures Patch/blotter shows coking
Wrong lubricant	Change in viscosity, VI, flash point, additive elements, FTIR[b] specta, TAN[c]/TBN[d] Change in wear patterns	Change in oil gage or bearing temperature Bearing distress or noise Hard turning of shaft
Antioxidant depletion	Decreasing TAN[c], RBOT oxidation life, and Zn/P content Increasing viscosity, TAN[c], particle count FTIR: decreasing antioxidant, increasing oxidation, sulphation, and/or nitration	Oil darkening Pungent odor Hot running

(a) Not all of the identified indications would be expected for each problem area; (b) Fourier Transform Infrared Spectroscopy; (c) Total Acid Number; (d) Total Base Number; (e) Vapor-Induced Scintillation Analysis; (f) Karl Fischer.
Reference: Reprinted by permission of Noria Corporation, Tulsa, OK.

(Continued)

Table 12-11 (Concluded)

Problem Area	Analytical Indications[a]	Inspection/Sensory Indications[b]
Dispersancy failure	FTIR[b], low TBN[d] Increasing particle count, pentane insolubles Defined inner spot on blotter test	Filter inspection: sludge on media, filter in bypass Black exhaust smoke Deposits on rings and valves
Base oil deterioration	Increasing viscosity, TAN[c], particle count, and/or ferrous particles Decreasing TBN[d] Change in VI and lower dielectric strength	Poor oil/water separability Air entrainment/foaming Pungent odor, sludge/varnish formation Blotter spot yellow/brown, oil darkening
Water contamination	Increasing viscosity, TAN[c], Ca, Ma, and/or Na Rapid additive depletion/failure Crackle test, VISA[e], KF[f], FTIR[b] Reduced dielectric strength Blotter test: sharp or star burst periphery on inner spot	Oil clouding/opacity, water puddling/separating, sludging, foaming Evidence of fretting wear/corrosion Filter: paper is wavy, high-pressure drop, short life; ferrogram shows rust Valve sticking, orifice silting, bearing distress/failure, noisy pump/bearings
Coolant contamination	Increasing viscosity, copper, particle count, wear metal, Na, B, and/or K FTIR[b], glycol Crackle test, VISA[e], KF[f]	Bearings dark charcoal color, distressed Dispersancy failure, sludging, varnishing Blotter test: sticky, black center Filter plugs prematurely, oil has mayonnaise consistency, white exhaust smoke
Fuel dilution	Low oil viscosity, flash point Additive and wear metal dilution (elemental analysis) FTIR[b]/gas chromatography for fuel Rising particle count and wear metals	Rising oil levels and oil gage temperatures Blotter test: halo around center spot Blue exhaust smoke (collapsed rings), plugged air filter, defective injectors Oil has diesel odor, overfueling conditions

(3) However, for most lubricating systems filter or purify oil periodically as dictated by the results of the oil testing program. Water is the most common contaminant found in hydroelectric plants, and its presence in oil may promote oxidation, corrosion, sludge formation, foaming, additive depletion, and generally reduce a lubricant's effectiveness. Solid contaminants such as dirt, dust, or wear particles also may be present. These solid particles may increase wear, and promote sludge formation, foaming, and restrict oil flow within the system. The following are some of the most common methods used to remove contaminants from oil.

b. Gravity purification. Gravity purification is the separation or settling of contaminants that are heavier than the oil. Gravity separation occurs while oil is in storage but is usually not considered an adequate means of purification for most applications. Other purification methods should also be used in addition to gravity separation.

c. Centrifugal purification. Centrifugal purification is gravity separation accelerated by the centrifugal forces developed by rotating the oil at high speed. Centrifugal purification is an effective means of removing water and most solid contaminants from the oil. The rate of purification depends on the viscosity of the oil in a container and the size of the contaminants.

d. Mechanical filtration. Mechanical filtration removes contaminants by forcing the oil through a filter medium with holes smaller than the contaminants. Mechanical filters with fine filtration media can remove particles as small as 1 micron, but filtration under 5 microns is not recommended because

Table 12-12
ISO 4406 Range Numbers

Number of Particles per Milliliter		
Greater Than	**Less Than**	**ISO 4406 Range Number**
80,000	160,000	24
40,000	80,000	23
20,000	40,000	22
10,000	20,000	21
5,000	10,000	20
2,500	5,000	19
1,300	2,500	18
640	1,300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8
0.64	1.3	7
0.32	0.64	6
0.16	0.32	5
0.08	0.16	4
0.04	0.08	3
0.02	0.04	2
0.01	0.02	1

Reference: Contamination Control and Filtration Fundamentals, Pall Corporation, Glen Cove, NY.

many of the oil additives will be removed. A typical mechanical filter for turbine oil would use a 6- to 10-micron filter. The filter media will require periodic replacement as the contaminants collect on the medium's surface. Filters have absolute, beta, and nominal ratings as follows:

(1) Absolute rating. Absolute rating means that no particles greater than a certain size will pass through the filter and is based on the maximum pore size of the filtering medium.

Table 12-13
Desirable Fluid System Cleanliness Levels

ISO Contaminations Code	System Sensitivity	Types of Systems and Typical Applications
15/13/9	Supercritical	Silt-sensitive control system with very high reliability. Laboratory apparatus, aerospace systems.
17/15/11	Critical	High-performance servo and high-pressure long-life systems, e.g., aircraft, machine tools, industrial robots.
19/16/13	Very important	High-quality reliable systems, e.g., turbo machinery (steam, gas, hydro), lube and electro-hydraulic controls, general machine requirements.
20/18/14	Important	General machinery and mobile hydraulic systems. Medium pressure, medium capacity. Acceptable in-service oil quality for steam turbines without lift pumps.
21/19/15	Average	Low oil pressure heavy-duty industrial system and construction equipment or applications where long life is not critical, e.g., winches, mobile heavy equipment transmissions.
23/21/17	Noncritical	Low-pressure systems with large clearances, e.g., ships' elevators.

Reference: Contamination Control and Filtration Fundamentals, Pall Corporation, Glen Cove, NY.

(2) Beta rating. The beta rating or beta ratio is a filter-rating expressed as the ratio of the number of upstream particles to the number of downstream particles of a particular size or larger. It expresses the separating effectiveness of a filter. The beta ratio counts the results from the multipass "beta" test for filters, ANSI/(NFPA) T3.10.8.8, and ISO 4572, "Hydraulic Fluid Power - Filters - Multi-Pass Method for Evaluating Filtration Performance."

(3) Nominal rating. Nominal rating is not an industry standard but an arbitrary value assigned by the filter manufacturer and means that a filter stops most particles of a certain micron size. Due to its imprecision, filter selection by nominal rating could lead to system contamination and component failure.

e. Coalescence purification. A coalescing filter system uses special cartridges to combine small, dispersed water droplets into larger drops. The larger water drops are retained within a separator screen and fall to the bottom of the filter while the dry oil passes through the screen. A coalescing filter will also remove solid contaminants by mechanical filtration.

f. Vacuum dehydration. A vacuum dehydration system removes water from oil through the application of heat and vacuum. The contaminated oil is exposed to a vacuum and is heated to temperatures of approximately 38 °C to 60 °C (100 °F to 140 °F). The water is removed as a vapor. Care must be exercised to ensure that desirable low-vapor-pressure components and additives are not removed by the heat or vacuum.

g. Adsorption purification. Adsorption or surface-attraction purification uses an active-type medium such as fuller's earth to remove oil oxidation products by their attraction or adherence to the large internal surfaces of the media. Because adsorption purification will also remove most of an oil's additives, this method should not be used for turbine oil purification.

h. Filter system. A system consisting of a vacuum purifier to remove the water, a centrifuge to remove large solid particles, and a 10-micron filter to remove the finer solid particles is the most desirable

Table 12-14
System Cleanliness Level Guidelines

Hydraulic System									
Servo Valve	A	B	C	D	E				
Proportional Valve		A	B	C	D	E			
VariableVolume Pump			A	B	C	D	E		
Cartridge Valve				A	B	C	D	E	
Fixed Piston Pump				A	B	C	D	E	
Vane Pump					A	B	C	D	E
Pressure/Flow Control Valve					A	B	C	D	E
Solenoid Valve					A	B	C	D	E
Gear Pump					A	B	C	D	E
Lubrication System									
Ball Bearings		A	B	C	D	E			
Roller Bearings			A	B	C	D	E		
Journal Bearings				A	B	C	D	E	
Gear Box (Industrial)				A	B	C	D	E	
Gear Box (Mobile)					A	B	C	D	E
Diesel Engine						A	B	C	D
Cleanliness Level (PCC)	12/10/7	13/11/9	14/12/10	15/13/11	16/14/12	17/15/12	17/16/13	18/16/14	19/17/14

Hydraulic system pressure (kPa) range- C > 172,500, D 10,350 to 17,250, E < 10,350
Lubrication system: Pressure ranges do not apply. Start at midrange C and adjust per following guidelines:
To determine system cleanliness level:

1. Starting at the top of the system component list. Find the first item used in hydraulic or lubrication system.
2. Locate box to the right of selected component, which corresponds to the operating pressure range.
3. Recommended cleanliness level is given at the bottom of each column that the box falls into.
4. Shift one column to the left if any of the following factors apply:
   a. System is critical to maintaining production schedules.
   b. High cycle/severe duty application.
   c. Water-containing hydraulic fluid is used.
   d. System is expected to be in service more than seven years.
   e. System failure can create a safety concern
5. Shift two columns to the left if two or more factors apply.
6. For lubrication systems, shift one column to the right if operating viscosity is greater than 500 SUS.
7. For flushing, shift one to two columns to the left.

Reference: Contamination Control and Filtration Fundamentals, Pall Corporation, Glen Cove, NY

system. The vacuum purifier should be specified as being suitable for the lubricating oil. The ability of a filter system to remove water is especially important to prevent microbial contamination in lubricants and hydraulic fluids. However, this type of system alone may not be sufficient. Introduction of biocides may be necessary to minimize the chemical reaction byproducts and contamination due to microbes.

i. Location and purpose of filters. Table 12-15 provides information on the location and purpose of filters. Table 12-16 lists various types of filters and the range of particle sizes filtered by each.

Table 12-15
Location and Purpose of Filter in Circuit

Location	Degree of Filtration	Type	Purpose
Oil reservoir vent	Coarse	Wire wool Paper Oil bath	Removal of airborne contaminant
Oil reservoir filler	Coarse	Gauze	Prevention of ingress of coarse solids
Suction side of pump	Medium	Paper Gauze	Protection of pump
Delivery side of pump	Fine	Sintered metal Felt Paper	Protection of bearings/system
Return line to reservoir	Medium	Gauze Paper	Prevention of ingress of wear products to reservoir
Separate from system	Very fine	Centrifuge	Bulk cleaning of whole volume of lubricant

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

Table 12-16
Range of Particle Sizes That Can be Removed by Various Filtration Methods

Filtration Method	Examples	Range of Minimum Particle Size Trapped Micrometers (μm)
Solid fabrications	Scalloped washers, wire-wound tubes	5-200
Rigid porous media	Ceramics and stoneware Sintered metal	1-100 3-100
Metal sheets	Perforated Woven wire	100-1000 5-200
Porous plastics	Plastic pads, sheets, etc. Membranes	3-100 0.005-5
Woven fabrics	Cloths of natural and synthetic fibers	10-200
Cartridges	Yarn-wound spools, graded fibers	2-100
Nonwoven sheets	Felts, lap, etc. Paper - cellulose - glass Sheets and mats	10-200 5-200 2-100 0.5-5
Forces	Gravity settling, cyclones, centrifuges	Sub-micrometer

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

12-11. Oil Operating Temperature

The recommended oil operating temperature range for a particular application is usually specified by the equipment manufacturer. Exceeding the recommended range may reduce the oil's viscosity, resulting in inadequate lubrication. Subjecting oil to high temperatures also increases the oxidation rate. As previously noted, for every 18 °F (10 °C) above 150 °F (66 °C), an oil's oxidation rate doubles and the oil's life is essentially cut in half. Longevity is especially critical for turbines in hydroelectric generating units where the oil life expectancy is several years. Ideally the oil should operate between 50 °C and 60 °C (120 °F and 140 °F). Consistent operation above this range may indicate a problem such as misalignment or tight bearings. Adverse conditions of this nature should be verified and corrected. Furthermore, when operating at higher temperatures, the oil's neutralization (acid) number should be checked more frequently than dictated by normal operating temperatures. An increase in the neutralization number indicates that the oxidation inhibitors have been consumed and the oil is beginning to oxidize. The lubricant manufacturer should be contacted for recommendations on the continued use of the oil when the operating temperatures for a specific lubricant are unknown. Figures 12-1 through 12-3 show relationships between hours of operation and temperature for mineral and synthetic oils and greases. Figure 12-4 shows base oil temperatures for mineral and synthetic lubricants. Figure 12-5 shows usable temperature range for greases. Table 12-17 shows pour point temperatures for mineral and synthetic lubricants. Table 12-18 shows practical high-temperature limits for solid lubricants.

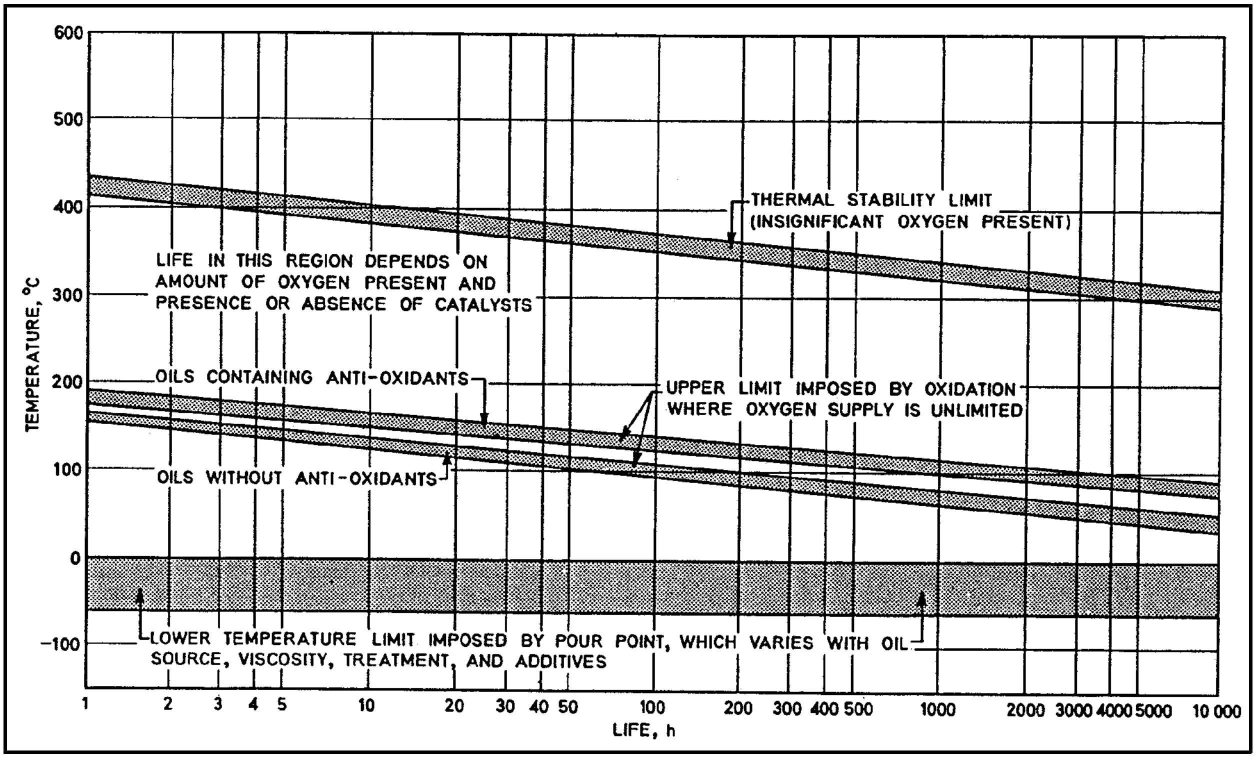


Figure 12-1. Temperature limits for mineral oils (Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)

12-12. Lubricant Storage and Handling

Lubricants are frequently purchased in large quantities and must be safely stored. The amount of material stored should be minimized to reduce the potential for contamination, deterioration, and health and explosion hazards associated with lubricant storage. Table 12-19 identifies the causes of lubricant deterioration and prevention during storage. Although lubricant storage receives due attention, equipment that has received a lubricant coating and stored is frequently forgotten. Stored equipment should be inspected on a periodic basis to ensure that damage is not occurring. Table 12-20 lists recommended frequency of inspection for stored equipment. Table 12-21 provides inspection and relubrication recommendations for equipment in storage.

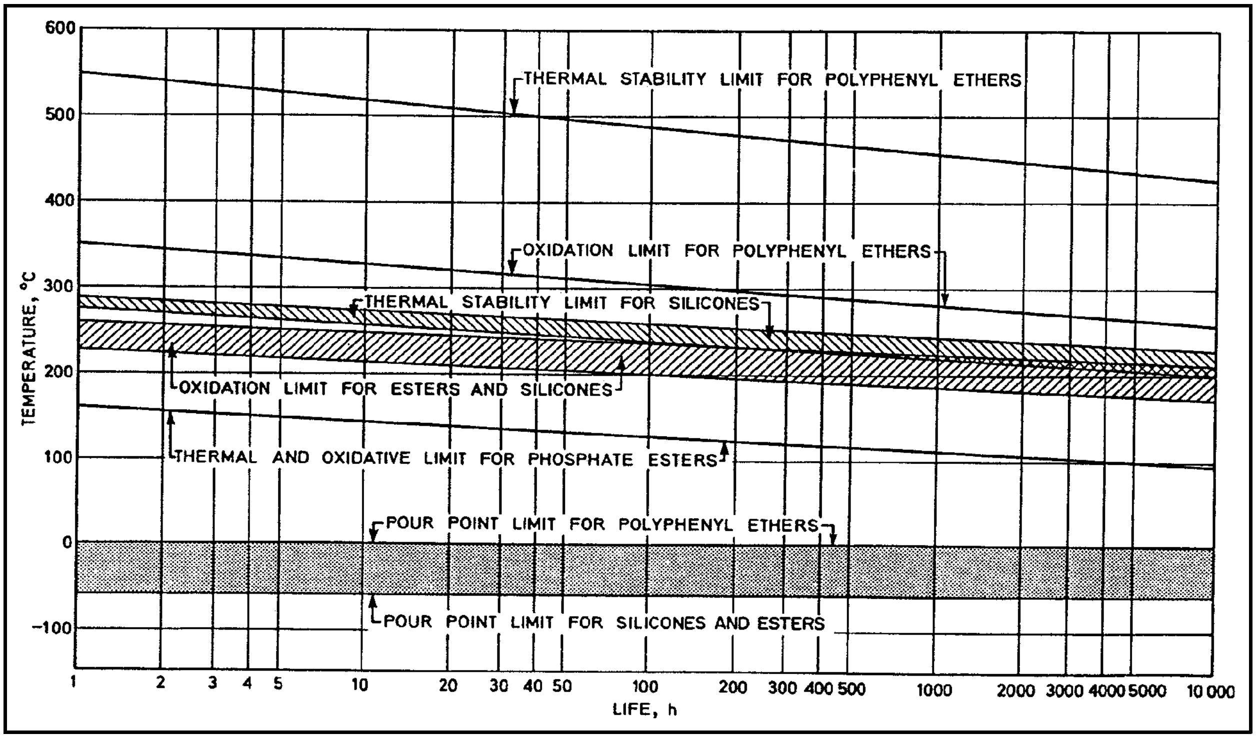


Figure 12-2. Temperature limits for some synthetic oils (Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)

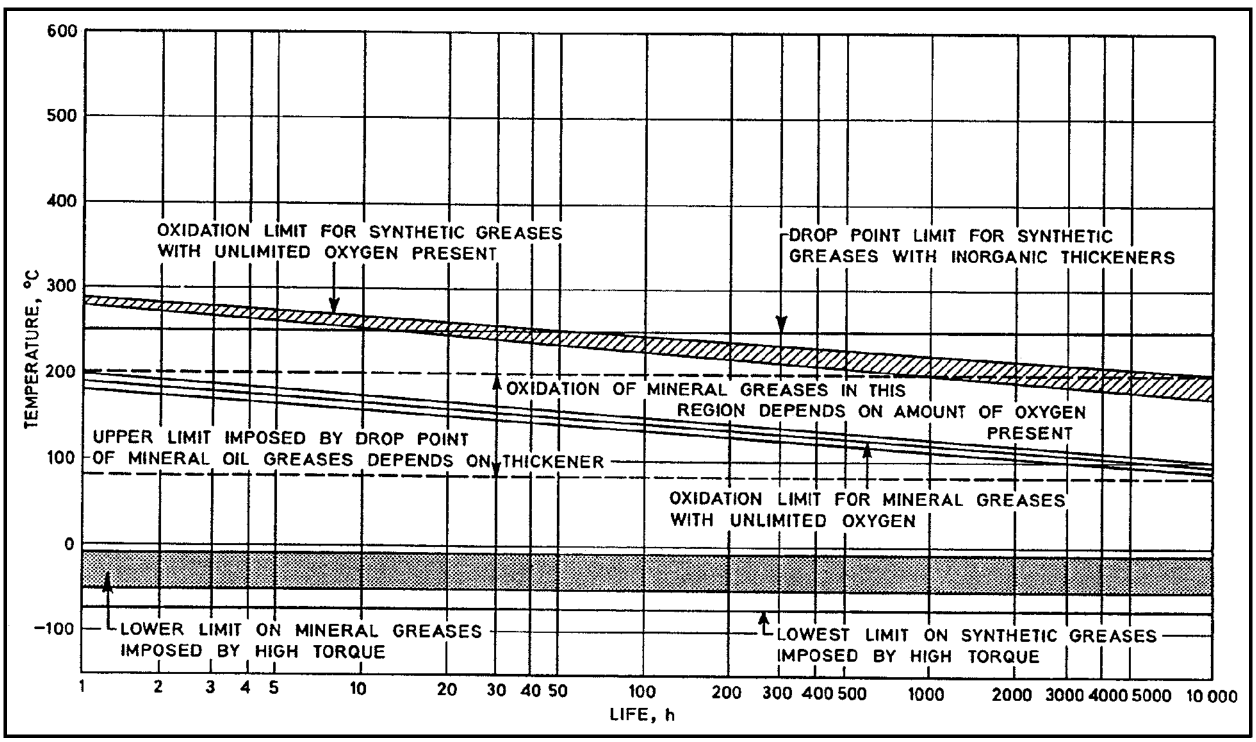
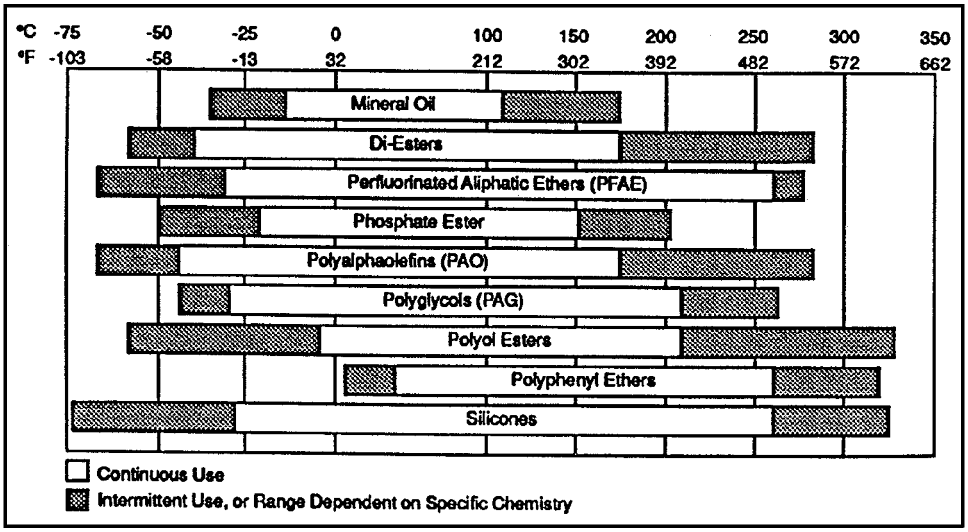


Figure 12-3. Temperature limits for greases (Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)



12-4. Base oil temperature limits (Reference: Booser, R.E., Reprinted with permission from CRC Handbook of Lubrication (Theory and Practice of Tribology); Volume II Theory and Design, Copyright CRC Press, Boca Raton, Florida)

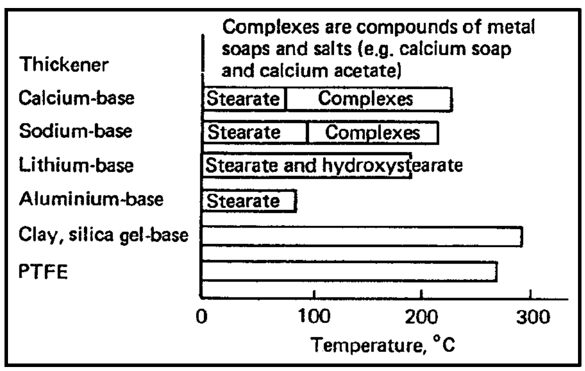


Figure 12-5. Usable temperature range for greases (Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)

Table 12-17
Lubricant Pour Point Temperatures

Type of Lubricant	Pour Point, ° C (°F)	
Mineral oil	-57 (min.)	(-70.6)
Diester	-60	(-76.0)
Phosphate ester	-57	(-70.6)
Silicate ester	-65	(-85.0)
Di-siloxane	-70	(-94.0)
Silicone	-70	(-94.0)
Polyphenyl-ether	-70	(-94.0)
Perfluorinated polyether	-75 to -90	(-103 to -130)

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England

Table 12-18
Temperature Limitations of Solid Lubricants

	Example	Practical Temperature Limit, ° C*	(°F)	Common Usages
1. Boundary lubricants and extreme pressure additives (surface active)	Metal soap (e.g., stearate)	150	(302)	Metal cutting, drawing, and shaping; Highly-loaded gears
	Chloride (as $Fe\ Cl_3$)	300	(572)	
	Sulphide (as FeS)	750	(1382)	
	Phthalocyanine (with Cu and Fe)	550	(1022)	Antiseizure
2. Lamellar solids and/or low shear strength solids	Graphite	600	(1112)	General, metal working, antiseizure, and antiscuffing
	Molybdenum disulphide	350	(662)	
	Tungsten disulphide	500	(932)	
	Lead monoxide†	650	(1202)	
	Calcium fluoride	1000	(1832)	
	Vermiculite	900	(1652)	Antiseizure
	PTFE	250	(482)	Low friction as bonded film or reinforced composite

* The limit refers to use in air or other oxidizing atmospheres.
† Bonded with silica to retard oxidation.
Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

a. Oil. Oil is stored in active oil reservoirs, where it is drawn as needed, and in oil drums for replenishing used stock. Each mode has its own storage requirements.

(1) Filtered and unfiltered oil tanks. Most hydroelectric power plants use bulk oil storage systems consisting of filtered (clean) and unfiltered (dirty) oil tanks to store the oil for the thrust bearings, guide bearings, and governors. Occasionally the filtered oil tank can become contaminated by water condensation, dust, or dirt. To prevent contamination of the bearing or governor oil reservoirs, the filtered oil should be filtered again during transfer to the bearing or governor reservoir. If this is not possible, the oil from the filtered tank should be transferred to the unfiltered oil tank to remove any settled contaminants. The filtered oil storage tank should be periodically drained and thoroughly cleaned. If the area where the storage tanks are located is dusty, a filter should be installed in the vent line. If water contamination is persistent or excessive, a water absorbent filter, such as silica gel, may be required.

(2) Oil drums. If possible, oil drums should be stored indoors. Store away from sparks, flames, and extreme heat. The storage location must ensure that the proper temperature, ventilation, and fire protection requirements are maintained. Tight oil drums breathe in response to temperature fluctuations, so standing water on the lid may be drawn into the drum as it “inhales.” Proper storage is especially important when storing hydraulic fluids due to their hygroscopic nature. To prevent water contamination, place a convex lid over drums stored outdoors. Alternatively, the drums should be set on their side with the bungs parallel to the ground. The bungs on the drums should be tightly closed except when oil is being drawn out. If a tap or pump is installed on the drum, the outlet should be wiped clean after drawing oil to prevent dust from collecting.

b. Grease. Grease should be stored in a tightly sealed container to prevent dust, moisture, or other contamination. Excessive heat may cause the grease to bleed and oxidize. Store grease in clean areas where it will not be exposed to potential contaminants, and away from excessive heat sources such as furnaces or heaters. The characteristics of some greases may change with time. A grease may bleed, change consistency, or pick up contaminants during storage. To reduce the risk of contamination, the

Table 12-19
Causes of Lubricant Deterioration and Their Prevention

Cause	Components Affected	Effect	Prevention
ATMOSPHERIC Oxygen	Lubricants	Forms gums, resins, and acidic products with viscosity increase.	Use lubricant containing antioxidation additive. Keep in sealed containers.
	Engines and components	When moisture is present, causes corrosion, particularly to ferrous components.	Coat with lubricant or temporary protective. Wrap in airtight packages using vapor phase inhibitors. In sealed units, include desiccants.
	Cables and wires	Corrosion in the presence of water.	Coat with lubricant or temporary protective.
	Seals	Promotes slow cracking of natural rubber and some similar materials. Negligible normally at ambient temperatures.	Use of a different polymer. Do not store in a hot place.
Pollutants (e.g., sulphur dioxide, hydrogen sulphide)	Engines and components Cables and wires Brakes and clutches	Rapid corrosion of most metals.	Store in sealed containers. Coat metals with temporary protective or lubricant. Filter air supply to remove pollutants.
Dust and Dirt	Lubricants	Increased rate of wear between bearing surfaces.	Keep covered or in containers.
	Engines and components Cables and wires Brakes and clutches	Increased rate of wear between bearing surfaces. Promotes corrosion in the presence of moisture	Keep covered or in containers
TEMPERATURE Heat	Lubricants	Increases rate of deterioration as under "Oxygen." Will increase oil separation from greases.	Keep store temperature no higher than 20° C (68 °F)
	Seals	Increases deterioration rate as above.	
Cold	Lubricants	In water-containing materials (e.g., cutting oils and certain fire-resisting hydraulic oils) water could separate out.	Keep temperature above freezing point
HUMIDITY	Seals	Could become brittle.	
	Engines and components Cables and wires	Promotes corrosion. More severe when ferrous and nonferrous metals present. See "Oxygen."	Coat metal parts with lubricant or temporary protective.
	Brakes and clutches Belts and ropes Seals	Promotes fungus/bacterial growth.	Store in dry location.
LIGHT	Lubricants	Promotes formation of gums, resins, and acidity.	Store in metal or opaque containers.
FUNGI/BACTERIA	Lubricants	Growth occurs at water/oil interface.	Keep water out of containers. In certain cases, biocides and fungicides can be added.
	Brakes and clutches Belts and ropes Seals	Surface covered and attacked by mold growth.	Store in dry location. Treat with biocide and fungicide.
VIBRATION	Engines and components	Ball bearings, and to a lesser extent roller bearings, suffer false brinelling.	Do not store where there is vibration. Resilient mountings can reduce effects of vibration.

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

Table 12-20
Frequency of Inspection

Component	How Stored	Inspect
Lubricants	Bulk tanks	Each year, and when refilled.
	Sealed containers	Check annually for damage to containers. Limited tests for serviceability of contents after 3 years.
Engines and components	General storage Packaged or sealed containers	Annually. Hand-turn engines where possible. Two to four years.
Cables and wires Brakes and clutches Belts and seals	General storage	Visual inspection annually.
Ropes	General storage	Turn annually and test to destruction
Rot proofed		Every 4 years
Untreated		Every 2 years
Synthetic fiber		Every 4 years

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

Table 12-21
Relubrication and Reprotection

Component	How Stored	Inspection and Treatment
In general:		
Engines and components	Coated with lubricant or temporary protective	Recoat annually. Lubricate when brought into use.
	Packaged or sealed containers	Replace VPI, desiccants, or lubricant every 2 to 4 years.
Special items:		
Grease-packed ball and roller bearing	After prolonged or adverse storage, or if oil bleeding has occurred	Before use, clean out old grease with solvent,* remove surplus solvent, and replace with new grease.
Oil-impregnated porous metal bearings	After prolonged or adverse storage	Before use soak in warm oil of the same type as originally impregnated.
Small mechanisms in their own cases, e.g., watches, servos	Coated with lubricant	Relubricate every 4 years.
Small mechanisms and components, e.g., gas bearings, watch components		These will require specialized cleaning and lubrication before being brought into use.
Cables and wires		Replace every 2 to 3 years.

* For example, paraffin, trichlorethylene.
Note: Traces of chlorinated solvents such as trichlorethylene, particularly in the presence of moisture, can cause corrosion of most metals. Therefore, after cleaning with chlorinated solvents all traces should be removed, ideally by blowing with warm dry air.
Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England

amount of grease in storage should not exceed a one-year supply. Before purchasing grease supplies, the manufacturer or distributor should be consulted for information about the maximum shelf life and other storage requirements for the specific grease.

12-13. Safety and Health Hazards

Safety considerations related to lubricants include knowledge of handling and the potential hazards. With this information, the necessary precautions can be addressed to minimize the risk to personnel and equipment.

a. Material safety data sheets. When handled properly, most lubricants are safe, but when handled improperly, some hazards may exist. Occupational Safety and Health Administrtion (OSHA) Communication Standard 29 CFR 1910.1200 requires that lubricant distributors provide a Material Safety Data Sheet (MSDS) at the time lubricants are purchased. The MSDS provides essential information on the potential hazards associated with a specific lubricant and should be readily accessible to all personnel responsible for handling lubricants. The lubricant's MSDS should provide information on any hazardous ingredients, physical and chemical characteristics, fire and explosion data, health hazards, and precautions for safe use.

b. Fire, explosion, and health hazards

(1) Oils. Although lubricating oils are not highly flammable, there are many documented cases of fires and explosions. The risk of an explosion depends on the spontaneous ignition conditions for the oil vapors (see Figures 12-6 and 12-7). These conditions can be produced when oils are contained in enclosures such as crankcases, reciprocating compressors, and large gear boxes.

(2) Hydraulic fluids. Hydraulic systems are susceptible to explosion hazards. A leaking hose under high pressure can atomize hydraulic fluid, which can ignite if it contacts a hot surface. Use of fire-resistant hydraulic fluids significantly reduces the risk of an explosion. Use of water-based hydraulic fluids can prevent ignition by forming a steam blanket at the hot spot or ignition source. Synthetic fluids are less flammable than mineral oils. Under normal circumstances, synthetic fluid will not support combustion once the ignition source has been removed. Table 12-22 summarizes the properties of water-based and synthetic hydraulic fluids and notes special precautions that must be taken when they are used.

(3) Health hazards. Lubricants also present health hazards when in contact with skin. Health hazards associated with lubricants include :

! Toxicity--Some additives contained in mineral oils may be toxic.

! Dermatitis--May be caused by prolonged contact with neat or soluble cutting oil.

! Acne--Mainly caused by neat cutting and grinding oils.

! Cancer--May be caused by some mineral oil constituents.

Material Safety Data Sheets for products should be reviewed carefully by personnel to ensure that the proper handling procedures are used.

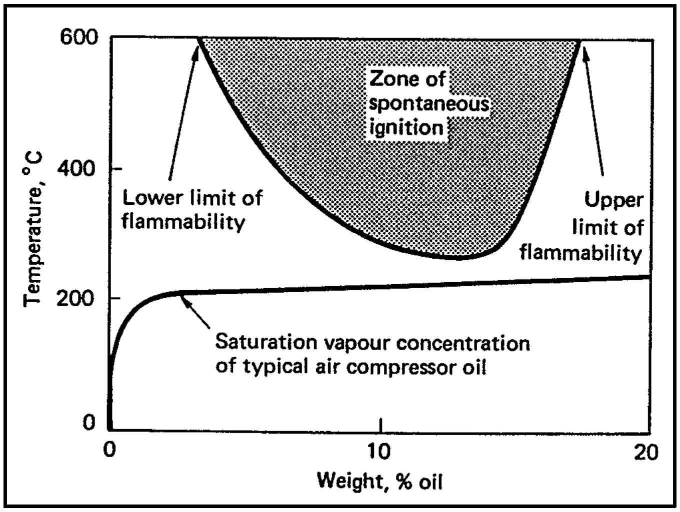


Figure 12-6. Spontaneous ignition limits for mineral oil vapor air mixtures at atmospheric pressure (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)

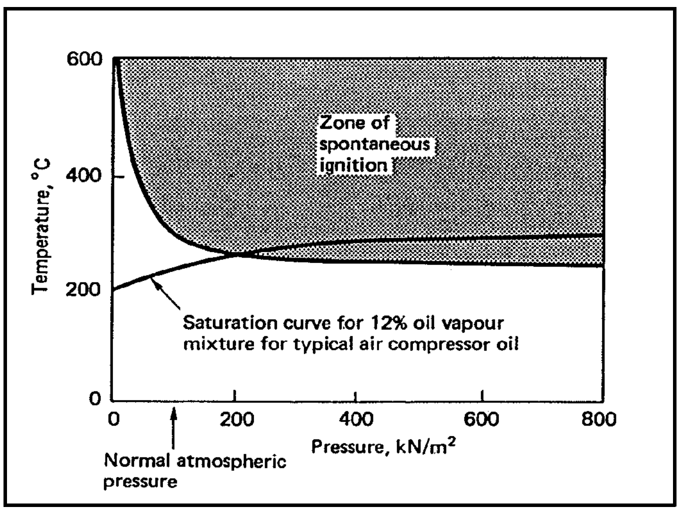


Figure 12-7. Spontaneous ignition limits for 12% mineral oil vapor as a function of pressure (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)

12-14. Environmental Regulations

a. Development of environmental regulations.

(1) Legislation passed by Congress is termed an Act of Congress. The responsibility for developing rules or regulations to implement the requirements of the Acts is given to various agencies of the Federal

Table 12-22
Fire-Resistant Hydraulic Fluids

	Water-containing Fluids			*Synthetic Fluids*	
	Soluble-oil Emulsions (2% Oil)	***Water-in-oil Emulsions (40% Water)***	***Water-glycol Blends (45% Water)***	***Phosphate Esters***	***Phosphate-ester Chlorinated Hydrocarbon Blends***
Maximum system temperature, °C (°F)	**65 (149)**	**65 (149)**	**65 (149)**	**100 (212)**	**100 (212)**
Restrictions on materials used in normal oil systems:					
(*I*) Internal paints	None	None	Special paints required	Special paints required	Special paints required
(ii) Rubber seals	None	None	Normally no problem	Special seals required	Special seals required
(iii) Materials of construction	None	None	Avoid magnesium, zinc, and cadmium plating	Avoid aluminum rubbing contacts	Avoid aluminum rubbing contacts
Lubrication:					
(I) Rolling bearings - apply factor to load for design calculations	Not suitable	2.0	2.5	1.2	1.2
(ii) Gear	Not recom-mended	Limit pressure to 3.5 MN/m^2 (500 lbf/in^2)	Limit pressure to 3.5 MN/m^2 (500 lbf/in^2)	Satisfactory	Satisfactory
Maintenance	---	Water content must be maintained*	Water content must be maintained	Should be kept dry	Should be kept dry
Cost relative to mineral oil	---	1.5-2	4-5	5-7	7-9

* Some separation of water droplets may occur on standing. The emulsion can, however, be readily restored by agitation. Care must be taken to avoid contamination by water-glycol or phosphate-ester fluids as these will cause permanent breakdown of the emulsion.
Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

Government such as the Environmental Protection Agency (EPA). The proposed regulations developed by these agencies are published daily in the Federal Register. After publication, the public is permitted to review and comment on the proposed regulations. All comments are evaluated after the specified review time (30 days, 60 days, etc.) has passed. The comments may or may not result in changes to the proposed regulations, which are published in the Federal Register as the final rules.

(2) The final rules from the Federal Register are compiled annually in the Code of Federal Regulations (CFR). The CFR is divided into 50 titles, numbered 1 through 50, which represent broad areas subject to Federal regulation. Title 40, “Protection of the Environment” contains regulations for the protection of the environment. References to the CFR are made throughout this subchapter. Copies of the CFR are not appended to this manual but can be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

(3) The general format for identifying a specific regulation in the CFR involves the use of a combination of numbers and letters. For example, 40 CFR 112.20, "Facility Response Plans,” indicates that the regulation is found in Title 40 of the CFR. It is further identified as Part 112. A part covers a

specific regulatory area, and can range in length from a few sentences to hundreds of pages. The number 20 that follows the decimal point indicates a given section where the specific information is found. A section also may range in length from a few sentences to many pages. Although not shown in this example, the section number may be followed by a series of letters and numbers in parentheses to further identify individual paragraphs.

(4) The regulations discussed in this subchapter are current at the time (1997) of writing. However, new regulations are being proposed and promulgated continuously. In addition, state or local regulations may be more restrictive than the Federal regulations, and must be reviewed carefully.

b. Water quality regulations. The Environmental Protection Agency (EPA) has developed water pollution regulations under legal authority of the Federal Water Pollution Control Act, also known as the Clean Water Act. These regulations are found in 40 CFR Subchapter D, “Water Programs,” and encompass Parts 100 through 149. Prominent parts of the regulation addressing oil pollution of the water are 40 CFR 110 “Discharge of Oil”; 40 CFR 112 “Oil Pollution Prevention”; and 40 CFR 113, “Liability Limits for Small Onshore Storage Facilities.”

(1) Reportable oil discharge. 40 CFR 110 requires the person in charge of a facility that discharges “harmful oil” to report the spill to the National Response Center (800-424-8802). The criteria for “harmful oil” discharges are:

(a) Discharges that violate applicable water quality standards.

(b) Discharges that cause a film or sheen upon or discoloration of the surface of the water or adjoining shorelines. Sheen means an iridescent appearance on the surface of the water.

(c) Discharges that cause a sludge or emulsion to be deposited beneath the surface of the water or adjoining shorelines.

(2) Spill Prevention Control and Countermeasures (SPCC) Plan. 40 CFR 112 requires regulated facilities that which have discharged or could reasonably discharge harmful oil into navigable U.S. waters or adjoining shorelines to prepare and implement a Spill Prevention Control and Countermeasures Plan. The regulation applies to nontransportation related facilities provided:

- The facility’s total above-ground oil storage capacity is greater than 5000 liters (1320 gallons), or the above-ground storage capacity of a single container is in excess of 2500 liters (660 gallons), or the total underground storage capacity of the facility is greater than 160,000 liters (42,000 gallons).

- Facilities which, due to their location, could reasonably expect spilled oil to reach U.S. waters.

(a) General requirements. 40 CFR 112.7 provides guidelines for preparing and implementing an SPCC plan. The SPCC plan is to follow the sequence outlined in the section and includes a discussion of the facility’s conformance with the appropriate guidelines. Basic principles to embody in an SPCC plan are:

- Practices devoted to the prevention of oil spills such as plans to minimize operational errors and equipment failures that are the major causes of spills. Operational errors can be minimized by training personnel in proper operating procedures, and increasing operator awareness of the imperative nature of spill prevention. Equipment failures can be minimized through proper construction, preventive maintenance, and frequent inspections.

! Plans to contain or divert spills or use equipment to prevent discharged oil from reaching navigable waters. When it is impracticable to implement spill containment measures, the facility must develop and incorporate a spill contingency plan into the SPCC plan.

! Plans to remove and dispose of spilled oil.

(b) Specific requirements

! Time limits. Prepare the SPCC within 6 months from startup. Implement the plan within 12 months from startup, including carrying out spill prevention and containment measures. Extensions may be authorized due to nonavailability of qualified personnel or delay in construction or equipment delivery beyond the control of the owner or operator. (40 CFR 112.3)

! Certification. A registered professional engineer must certify the SPCC and amendments. (40 CFR 112.3)

! Plan availability. Maintain a complete copy of the SPCC at an attended facility or at the nearest field office if the facility is not attended at least 8 hours per day. (40 CFR 112.3)

! Training. Conduct employee training on applicable pollution control laws, rules and regulations, proper equipment operation and maintenance to prevent oil discharge, and conduct spill prevention briefings to assure adequate understanding of the contents of the SPCC plan. (40 CFR 112.7)

! Plan review. Review the SPCC at least once every three years. (40 CFR 112.5)

! Amendments. Certified amendments to the SPCC are required when:

  ! The EPA Regional Administrator requires amendment after a facility has discharged more than 3785 liters (1000 gallons) of oil into navigable waters in a single spill event or discharged oil in harmful quantities into navigable waters in two spill events within any 12-month period. (40 CFR 112.4)

  ! There is a change in design, construction, operation, or maintenance that affects the potential for an oil spill. (40 CFR 112.5)

  ! The required 3-year review indicates more effective field proven prevention and control technology will significantly reduce the likelihood of a spill. (40 CFR 112.5)

(3) Facility response plans. 40 CFR 112.20 requires facility response plans to be prepared and implemented if a facility, because of its location, could reasonably be expected to cause substantial harm to the environment by discharging oil into or on navigable waters or adjoining shorelines. This regulation applies to facilities that transfer oil over water to or from vessels and have a total oil storage capacity greater than 160,000 liters (42,000 gallons), or the facility's total oil storage capacity is at least 3.78 million liters (1 million gallons) with conditions. Most Corps of Engineers civil works facilities do not fall under these categories.

(4) Liability limits. 40 CFR 113 establishes size classifications and associated liability limits for small onshore oil storage facilities with fixed capacity of 160,000 liters (1000 barrels, or 42,000 gallons) or less that discharge oil into U.S. waters and removal of the discharge is performed by the U.S. Government. Unless the oil discharge was a result of willful negligence or willful misconduct, the table in 40 CFR 113.4 limits liability as follows:

(a) Above-ground storage.

Size Class	Capacity (barrels)	Limit (dollars)
I	Up to 10	4,000
II	11 to 170	60,000
III	171 to 500	150,000
IV	501 to 1,000	200,000

(b) Underground storage.

Size Class	Capacity (barrels)	Limit (dollars)
I	Up to 10	5,200
II	11 to 170	78,000
III	171 to 500	195,000
IV	501 to 1,000	260,000

c. Soil quality regulations. Regulations regarding oil contamination of soil vary from state to state. State and local laws and regulations should be reviewed for guidelines on preventing and handling soil contamination from oil spills.